Lambda over Kaon Enhancement in Heavy Ion Collisions at Several TeV

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We introduced recently a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. Important for the particle production at intermediate values of transverse momentum (p_t) are jet-hadrons produced inside the fluid. They pick up quarks and antiquarks (or diquarks) from the thermal matter rather than creating them via the Schwinger mechanism – the usual mechanism of hadron production from string fragmentation. These hadrons carry plasma properties (flavor, flow), but also the large momentum of the transversely moving string segment connecting quark and antiquark (or diquark). They therefore show up at quite large values of p_t, not polluted by soft particle production. We will show that this mechanism leads to a pronounced peak in the lambda / kaon ratio at intermediate p_t. The effect increases substantially with centrality, which reflects the increasing transverse size with centrality.

Heavy ion collisions at relativistic energies are expected to lead to the formation of a quark gluon plasma, which strongly interacts and behaves as a fluid [1–4]. Nevertheless it is difficult to directly observe the plasma properties, since the fluid hadronizes and the corresponding hadrons still interact among themselves before being detected. It is therefore desirable to find observables which keep information about the partonic system despite the hadronization procedure. In this paper we will discuss in which sense the transverse momentum dependence of the lambda over kaon ratio is such an observable.

As already observed earlier in AuAu scattering at 200 GeV [5], also in PbPb collisions at 2.76 TeV there is an impressive increase of the lambda yield compared to kaons, more and more pronounced with increasing centrality, as shown by the ALICE collaboration [6]. This phenomenon concerns transverse momenta (p_t) in the range between 2 and 6 GeV/c. This so-called "intermediate p_t range" is the domain of coalescence models [7–11], where hadrons are produced by recombining quarks from the plasma, to be distinguished from "fragmentation" of partons. However, a detailed quantitative understanding of the intermediate p_t region is still missing, and as discussed in [12], it seems impossible to really separate an "intermediate p_t region" from the low and high transverse momentum domain.

In ref. [12], we introduced a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. The whole transverse momentum range is covered, from very low to very high p_t. In [12], we show that the new approach can accommodate spectra of jets with p_t up to 200 GeV/c in pp scattering at 7 TeV, as well as particle yields and harmonic flows with p_t between 0 and 20 GeV/c in PbPb collisions at 2.76 TeV. Since out aim is a single model which is able to cover all phenomena, we will apply the approach of ref. [12], with exactly the same parameters (EPOS2.17v3), to study lambda and kaon production, and try to understand the "lambda over K peak".

Let us briefly recall the essential features of the new approach, which are relevant for the discussion of this paper.

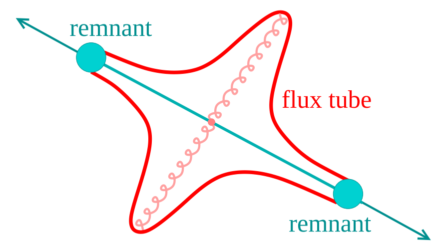

Figure **1**: (Color online) A single hard scattering, leading to two flux tubes with transversely moving parts (kinky strings).

All the details can be found in [12]. The basis are multiple scatterings (even for pp), where a single scattering is a hard elementary scattering plus initial state radiation, the whole object being referred to as parton ladder. The corresponding final state partonic system amounts to (usually two) color flux tubes, being mainly longitudinal, with transversely moving pieces carrying the p_t of the partons from hard scatterings. These flux tubes constitute eventually both bulk matter (which thermalizes, flows, and finally hadronizes) and jets, according to some criteria based on partonic energy loss.

Let us take the simple case of a single hard scattering producing two gluons, without initial state radiation. This leads to two flux tubes, with one transversely moving piece each, corresponding to the hard gluons, as shown in fig. 1. These flux tubes do not only cover central rapidities, since they stretch from projectile to target remnant. Including initial state radiation (which is automatically included in all calculations), will add more transversely moving pieces, leading to a complicated three-dimensional dynamics. But despite the complicated details, the flux tubes remains essentially longitudinal, with some transversely moving parts (kinks in the string language). The Flux tubes (strings) will expand and at some stage break via the production of quark-antiquark

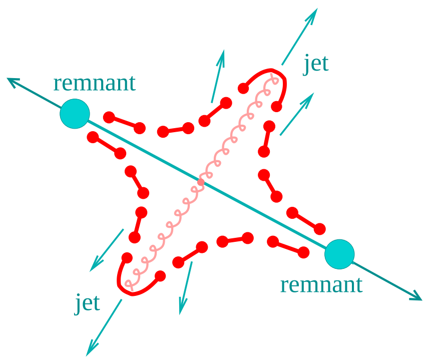

Figure **2**: (Color online) Flux tube breaking via $q-\bar{q}$ production, which screens the color field (Schwinger mechanism).

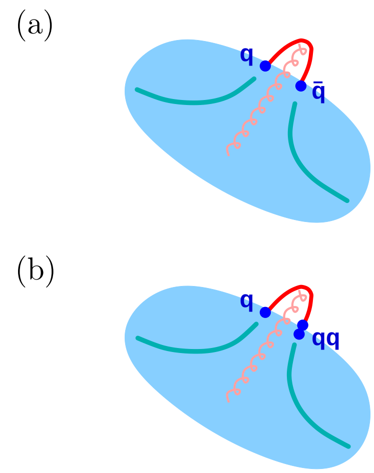

Figure **3**: (Color online) Escaping string segment, getting it's endpoint partons from the fluid. We show the case of a quark and an antiquark (a) and of a quark and a diquark (b). The rest of the string dissolves in matter.

or diquark-antidiquark pairs, as seen in fig. 2. The string segments are identified with hadrons. Those close to the transversely moving pieces carry the large momentum coming from the partons of the hard scattering – they constitute the jets, indicated by the arrows in fig. 2.

In heavy ion collisions and also in high multiplicity events in proton-proton scattering at very high energies, there are many elementary scatterings, and therefore many flux tubes. Their density will be so high that they cannot decay independently as described above. Here we have to modify the procedure as discussed in the following. The starting point are still the flux tubes (kinky strings) originating from elementary collisions, as discussed above. These flux tubes finally constitute both, bulk matter which thermalizes and expands collectively, and jets. The criterion which decides whether a string piece ends up as bulk or jet, is based on energy loss. In the following, we consider a flux tube in matter, where "matter" first means the presence of a high density of other flux tubes, which then thermalize.

Three possibilities occur: (A) String segments which have not sufficient energy to escaspe will constitute matter, they loose their character as individual strings. This matter will evolve hydrodynamically and finally hadronize ("soft hadrons"). (B) String segments having sufficient energy to escape and being formed outside the matter, constitute jets ("jet-hadrons"). (C) There are finally also string segments produced inside matter or at the surface, but having enough energy to escape and show up as jets ("jet-hadrons"). They are affected by the flowing matter ("fluid-jet interaction").

The criterion for a string segment to leave the matter or not, is based on energy loss, as discussed in[12]. In case (B), high energy flux tube segments will leave the fluid, providing jet-hadrons via the usual Schwinger mechanism of flux-tube breaking caused by quark-antiquark or diquark-antidiquark production.

Interesting is case (C). The jet-hadrons are produced still inside matter or at the surface, but they escape. Here we assume that the quark, antiquark, diquark, or antidiquark needed for the flux tube breaking is provided by the fluid with properties (momentum, flavor) determined by the fluid rather than the Schwinger mechanism, whereas the rest of the string dissolves in matter, see fig. 3. Considering transverse fluid velocities up to 0.7c, and thermal parton momentum distributions, one may get a "push" of a couple of GeV to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate p_t jet-hadrons and explains azimuthal asymmetries up to quite large values of p_t, as discussed in very detail in [12].

Even more important for the present discussion are two other effects: The quark (antiquark) flavors are determined from Bose-Einstein statistics, with more strangeness production compared to the Schwinger mechanism. And the probability p_{diq} to have a diquark rather than an antiquark will be bigger compared to a highly suppressed diquark-antidiquark breakup in the Schwinger picture (p_{diq} is a parameter).

All these effects are important concerning lambda and kaon production. In fig. 4, we show transverse momentum spectra for lambdas and kaons for central rapidities in central and peripheral PbPb collisions at 2.76 TeV. The spectra for the calculations without hydrodynamic evolution (pure string decay) are quite similar for lambdas and kaons, they essentially differ by a factor, simply due to the fact that the relative probability of diquark-antidiquark to quark-antiquark breakup is small. However, the situation is completely different, in case of the full calculation. Both lambdas and kaons increase at intermediate p_t, but

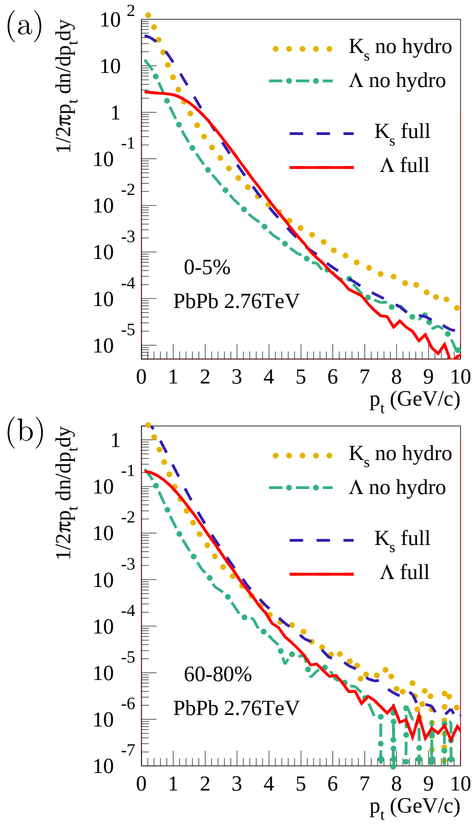

Figure **4**: (Color online) Transverse momentum spectra for lambdas and kaons (K_s) for central rapidities in central (a) and peripheral (b) PbPb collisions at 2.76 TeV. We show the full model calculations, and also the ones without hydro evolution.

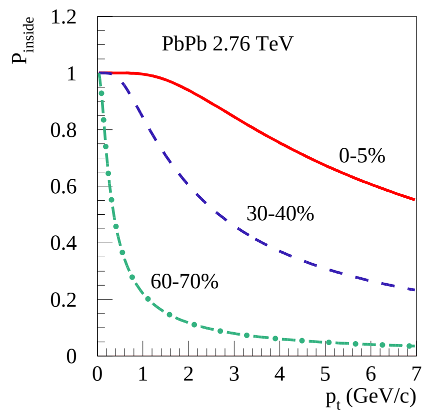

Figure **5**: (Color online) The estimate $P_{\rm inside}$ of the probability to form (pre)hadrons inside the fluid (in the direction parallel to the impact parameter), as a function of p_t, for PbPb collisions at 2.76 TeV. We show the curves for the 0-5%, the 30-40%, and the 60-70% most central events.

much more in case of lambdas. This is first of all due to flow, which pushes the heavier lambdas more than the kaons.

The effect is magnified due to jet-hadrons carrying fluid properties (process (C)): There is an additional momentum push from the fluid-jet interaction, which favors lambdas over kaons, due to the higher number of quarks of the former ones. Also the yield of lambdas is increased compared to kaons, because diquarks compared to quarks are less suppressed when taken from the fluid as compared to the Schwinger mechanism.

The effects are similar in central and peripheral PbPb collisions, but the preferred lambda production compared to kaons is more pronounced in the central compared to the peripheral events: the lambda curve crosses the kaon one in case of central, but not in case of peripheral collisions. The reason is that the number of jet-hadrons carrying fluid properties depends on their formation times: these hadrons must have been formed inside the fluid. In fig. 5, we plot the estimate $P_{\rm inside}$ of the probability to form (pre)hadrons inside the fluid, as a function of p_t, for different centralities (see [12]). This probability decreases strongly towards peripheral collisions, because the transverse sizes get much smaller. So we get less lambda enhancement at more peripheral collisions, and the enhancement is also shifted to smaller p_t.

In fig. 6, we show the lambda over kaon ratio as a function of p_t in PbPb collisions at different centralities. Our calculations (full symbols) follow quite well the trend seen in the data (open symbols): going from peripheral towards central collisions, one observes a more and more pronounced peak, which also moves to higher p_t. The calculations would fit the data even better with a slightly smaller formation time, but we prefer to use the parameters of ref. [12], which give quite good agreement with many other data sets.

To summarize: We introduced a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. This approach covers the whole transverse momentum range, from very low to very high p_t. In this framework, we can reproduce the experimentally observed strong increase of the lambda over kaon ratio at intermediate values of p_t. We understand this effect to be due to a communication between the fluid and jet-hadrons: these hadrons are composed of a high p_t string segment (from the hard process) and (di)quarks from the fluid, carrying fluid properties. So the final hadrons are observed at relatively high p_t, but nevertheless providing information about the fluid, whereas the soft hadrons from fluid freeze out carry only small p_t. The reason for the strong centrality dependence is the fact that the number of jet-hadrons having suffered a fluid-jet interaction depends on the volume: the probability that such a jet-hadron is produced inside the fluid is more likely for big volumes

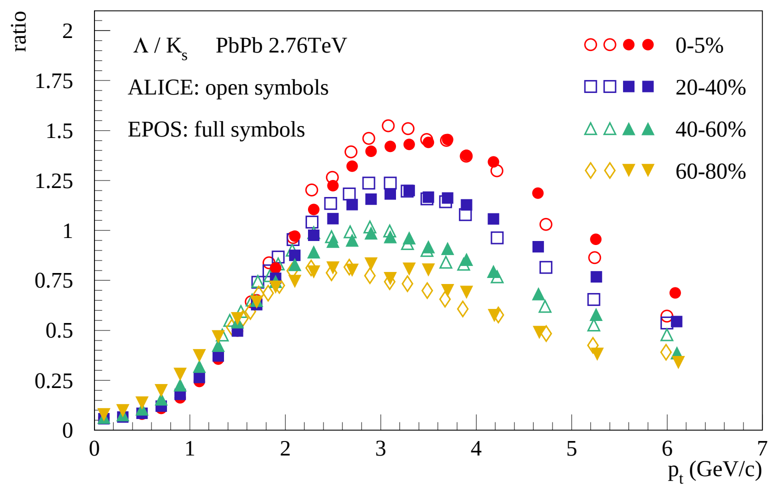

Figure **6**: (Color online) Lambda over kaon ratio as a function of p_t in PbPb collisions at different centralities. We show our theoretical results (full symbols) and data from ALICE [6] (open symbols).

compared to small ones. The fact that the enhancement disappears for very peripheral collisions does not mean that there is no fluid. It means that the volume is too small for this particular effect to be seen.

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